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WEAR COEFFICIENTS

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INTRODUCTION

Other chapters have revealed that wear is extremely complicated. For example the temperature can rise, thus increasing the thickness or changing the nature of the oxide layer. Alternatively, plastic deformation or fatigue can damage the material, increasing its tendency to wear. Thus, prediction of the wear rate to any high degree of accuracy (say ± 10%) has so far defied all attempts, even in cases where the sliding system is well understood and well controlled.

However, the task is much easier when we are content with an estimate of the wear rate within a factor of four or five. In this case the exact contributions of some of the complicating factors are less significant and leave the order of magnitude of the wear rate unaffected.

Wear predictions, even though imperfect, can be used in a number of ways besides estimating the wear rate. First, an equation for wear indicates the relative influence of various parameters, such as load, hardness, velocity, surface roughness and grain size, and suggests the change in wear that might result if the sliding system is changed. Second, computation of the wear is also important in failure analysis, or in the study of any worn component of a system.

Quantitative analysis of wear starts with the concept that, while a sliding system may be losing material in more than one way, one mechanism will dominate the overall wear rate. This dominant mechanism is generally identified as one of the following:

1. Adhesive wear — considered as 'mild' or 'severe' depending on the rate of wear and the size of the wear debris. In this case wear results from adhesion and pulling out of regions of one sliding surface by the other (see the chapter on Metallic Wear for further details of wear mechanisms).
2. Abrasive wear — results from a hard sharp object, which may be a loose abrasive particle or a sharp projection on one of the sliding surfaces, scratching out a groove in a sliding surface.
3. Corrosive wear — caused by mechanical removal of a surface layer formed by a corrosion process.
4. Surface fatigue wear — removal of particles loosened by a growth of surface or subsurface fatigue cracks arising from stress variations dueing continued sliding.

ADHESIVE WEAR

This principal form of wear is invariably present when two surfaces slide together, and adhesive wear is predominant in many cases where wear occurs by more than one mechanism. Adhesive wear has been investigated most intensely, probably because the same interatomic forces at the interface which cause adhesive wear also cause friction.

Although a number of studies have investigated the mechanism accounting for the formation of adhesive wear particles[1,2,3,4] only one simple quantitative relationship has been developed for predicting the wear rate. This is the equation derived by Holm[5] and refined by Archard.[1]

$$\text{Wear volume } V = \frac{k \times \text{normal load } L \times \text{distance slid } X}{\text{hardness } p} \qquad (1)$$

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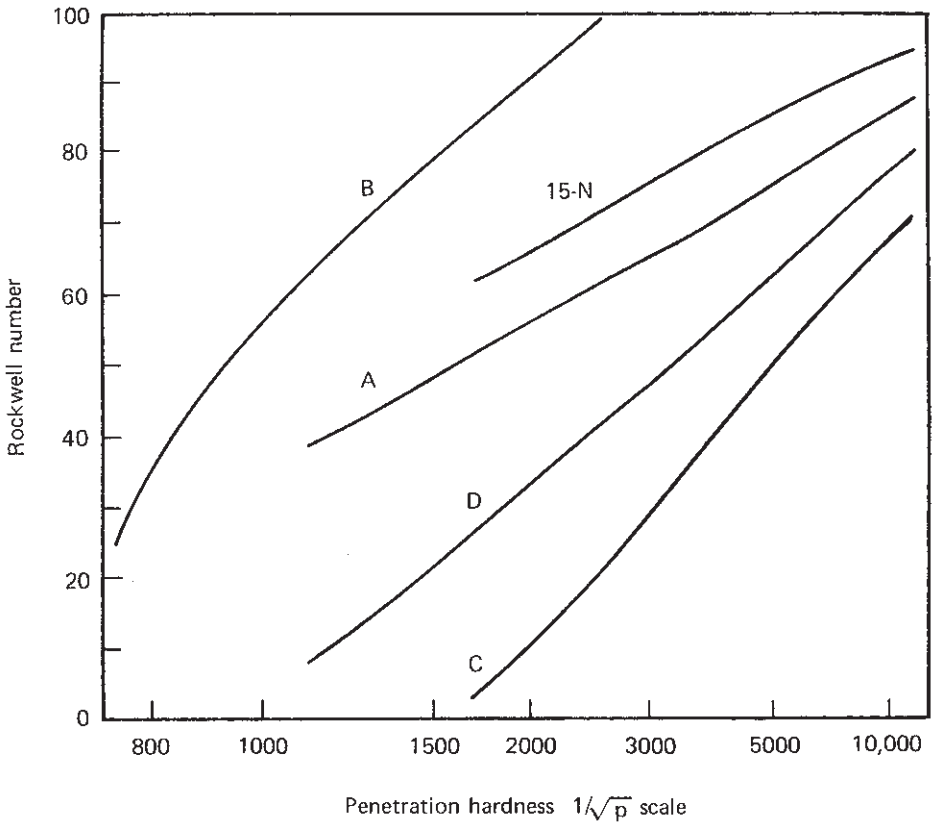

FIGURE 1. Diagram to help convert various Rockwell arbitrary hardness numbers into hardness stresses, p, in units of N/mm^2.

Here p represents indentation hardness, i.e., the ratio of load applied to area of indentation produced by plastic yielding, of the softer material being worn. Parameter k is a non-dimensional constant, the wear coefficient. In Archard's original derivation with a factor of three in the denominator of Equation 1, the wear coefficient physically represented the probability that a sizeable wear particle was produced during the contact of the two surfaces at an asperity. Data presented in this section are based on Equation 1 (i.e., the wear equation without the factor of three) for simplicity. Note that such parameters as surface roughness, grain size, sliding velocity, and apparent pressure do not appear in Equation 1. The wear is independent of them, except insofar as they influence other parameters (e.g., the distance slid is proportional to velocity).

The indentation hardness is best measured by a Vickers, Knoop, or Brinell hardness test. The number given in one of these tests is the hardness in units of kg/mm^2, and must be multiplied by 9.8 to convert to N/mm^2. The various Rockwell scales are arbitrary. Conversion to N/mm^2 may be made using Figure 1. The hardness of a material is about 3.2 times the yield stress in uniaxial tension or compression.

All terms in the wear equation, except k, are readily available parameters like load or material hardness. Thus, the key factor in determining the adhesive wear to be expected in any sliding situation is a knowledge of the only unknown, the wear coefficient k.

VALUES OF WEAR COEFFICIENT k

Very few investigations have been carried out with the primary aim of generating wear

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Table 1
WEAR COEFFICIENTS FOR UNLUBRICATED SURFACES

Material combination	Wear coefficient (k)
Low carbon steel on low carbon steel	70×10^{-4}
60/40 Brass on tool steel	6
Teflon® on tool steel	0.25
70/30 Brass on tool steel	1.7
Lucite on tool steel	0.07
Molded bakelite on tool steel	0.024
Silver steel on tool steel	0.6
Beryllium copper on tool steel	0.37
Tool steel on tool steel	1.3
Stellite #1 on tool steel	0.55
Ferrilic stainless steel on tool steel	0.17
Laminated bakelite on tool steel	0.0067
Tungsten carbide on low carbon steel	0.04
Polyethylene on tool steel	0.0013
Tungsten carbide on tungsten carbide	0.01

From Archard, J. F. and Hirst, W., *Proc. R. Soc. London Ser. A,* 236, 397. 1956. With permission.

Table 2
WEAR COEFFICIENTS FOR ADHESIVE WEAR

	Metal-on-metal				
Lubrication	**Identical**	**Soluble**	**Intermediate**	**Insoluble**	**Metal-on-nonmetal Nonmetal-on-nonmetal**
None	1500×10^{-6}	500×10^{-6}	100×10^{-6}	15×10^{-6}	3×10^{-6}
Poor	300	100	20	3	1.5
Good	30	10	2	0.3	1
Excellent	1	0.3	0.1	0.03	0.5

coefficient data. One experimental study was that of Archard and Hirst[6] and the results are shown in Table 1. The second[7] consisted of gathering the few wear coefficient values available from published papers, and this led to the information in Table 2. The utility of these wear coefficients is leading more and more to their use in reporting specific machine element and material test results.[8]

The two tables represent two different approaches to compiling wear coefficient data. Table 1 lists typical data, and then a user must find a value that is representative of his sliding conditions. In view of the endless variety of sliding, such a tabulation would have to be extremely extensive for general use. The other approach divides all sliding systems into a limited number of categories, and then gives appropriate wear coefficient data for each category. This approach is used in the present chapter.

For sliding metals, the two factors which mainly determine the value of the wear coefficient are the degree of lubrication and the metallurgical compatibility as indicated by the mutual solubility. The metallurgical compatibility represents the degree of intrinsic attraction of the atoms of the contacting metals for each other. Such compatibility is best determined from binary metal phase diagrams, which show the extent of mutual solubility or insolubility in the liquid or solid states.

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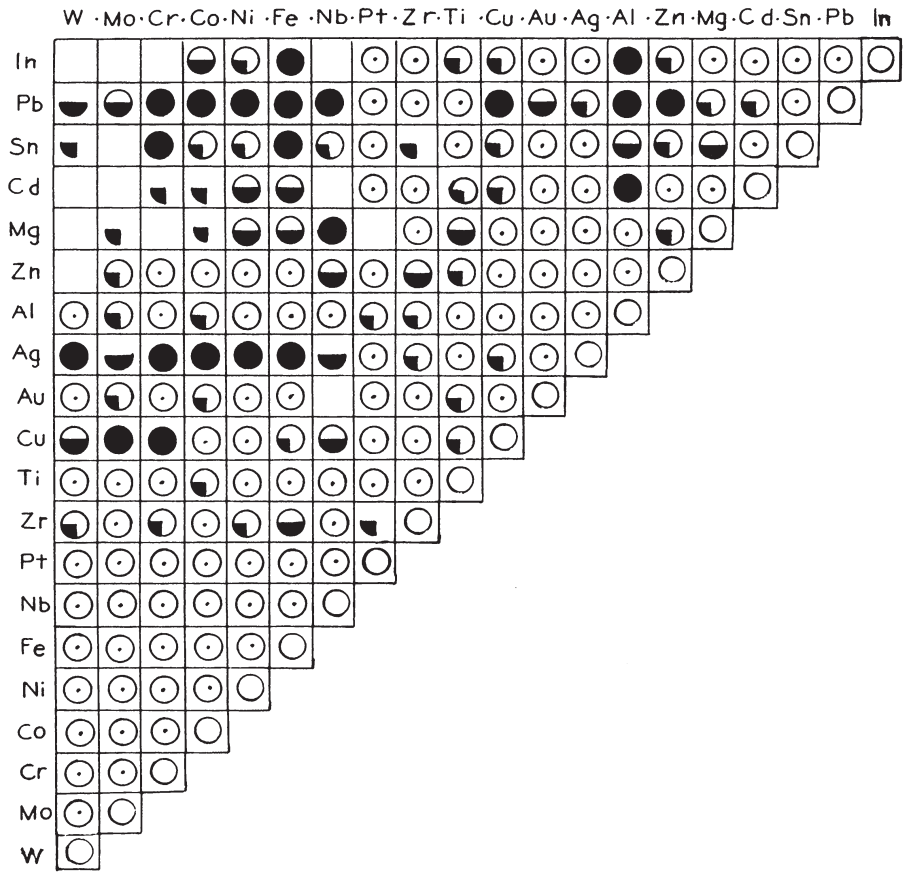

FIGURE 2. Compatibility diagram for metal pairs. The significance of the various circles is shown in Table 3. Partial circles and blank squares are due to insufficient information.

Table 3
COMPATIBILITY RELATIONSHIPS FOR METALS

Symbol	Metallurgical solubility	Metallurgical compatibility	Sliding compatibility	Anticipated wear
○	100%	Identical	Very poor	Very high
⊙	Above 1%	Soluble	Poor	High
◔	0.1—1%	Intermediate soluble	Intermediate	Intermediate
◒	Below 0.1%	Intermediate insoluble	Intermediate or good	Intermediate or low
●	Two liquid phases	Insoluble	Very good	Very low

The compatibility of a large number of metal pairs is shown in Figure 2.[9] The significance of the various circles, in terms of metallurgical solubility at room temperature, liquid miscibility, metallurgical compatibility, sliding compatibility, and anticipated wear are shown in Table 3. The general rule is that the blacker the circle, the better the sliding characteristics and the lower the adhesive wear coefficient.

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Four degrees of lubrication are considered in Table 2. The 'unlubricated' case assumes that the sliding surfaces are clean and slide without the presence of any introduced lubricant or contaminant. The second condition, labeled 'poor lubrication', assumes that the surfaces are covered by a poor lubricant, for example an inert fully fluorinated hydrocarbon, water, or gasoline. The third condition assumes the presence of a good lubricant such as mineral oil with lubricity additives. The fourth condition, excellent lubrication, is one in which excellent lubricants such as those containing zinc dialkyl dithiophosphate are used at moderate pressures and temperatures, so that surface burnishing occurs rather than wear particle formation on a large scale.

The wear coefficient values of Table 2 are based on experimental work[10] designed to generate wear data, as well as on published and unpublished wear data. Note that nonmetals sliding against metals or against nonmetals give similar wear coefficients, and these are indicated in the last column.

In applying the data of Table 2 to practical situations, two points come up. First, the solubility of an alloy is generally that of its major constituent. Thus, the rating of an aluminum bronze (copper 75%, aluminum 25% by volume) sliding against a stainless steel (iron 74%, chromium 18%, nickel 8%, by volume) is the same as that of copper against iron, namely intermediate. Second, when a liquid is heated its performance as a lubricant deteriorates above a characteristic transition temperature. For mineral oils this temperature is around 160°C. If the interfacial temperature is above 160°C, we use the wear value for the next higher line (e.g., a good lubricant above 160°C acts like a poor lubricant at room temperature).

To assist in using Equation 1, we show a simple example.

Illustrative Example 1

Problem

A person is writing with a pencil containing a 'lead' of Vickers hardness 5 kg/mm^2. If the writing force pressing the pencil against the paper is 0.5 N, estimate the volume of wear in writing a five-page letter (assuming that each page corresponds to 20 m of pencil-paper sliding).

Solution

The wear coefficient for unlubricated nonmetals is 3×10^{-6} (Table 2). The total sliding distance is $5 \times 20 \times 1000 = 10^5$ mm. The hardness of the pencil is 5×9.8 or 49 N/mm^2. The normal force is given as 0.49 N. On substitution in Equation 1,

$$V = \frac{3 \times 10^{-6} \times 0.5 \times 10^5}{49} = 3.1 \times 10^{-3}\,\text{mm}^3$$

Table 2 demonstrates the very large range of wear coefficients encountered in practice, ranging over about five orders of magnitude. Changes of the compatibilities of the surfaces may change the wear by two orders of magnitude, while changing the state of lubrication can affect the wear by as much as three orders of magnitude.

The condition described as excellent lubrication, in which the surfaces experience very little wear and become burnished, is not readily attainable. For like or compatible metals it is hardly possible to achieve excellent lubrication except when there is combined rolling and sliding, as in spur gears. With intermediate and insoluble metals, burnishing is generally possible if the mean interfacial pressure is less than 0.05 of the hardness stress of the softer material.

Lubricants have much less effect on the wear coefficient of nonmetals than on metals. Nonmetals when unlubricated give lower wear coefficients than metals, but the reverse is true in the presence of excellent lubricants.

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Table 4
ABRASIVE WEAR COEFFICIENTS

	Coefficient of wear (k)			
	File (new)	**Abrasive paper (new)**	**Loose abrasive grains**	**Coarse polishing**
Dry surfaces	50×10^{-3}	10×10^{-3}	1×10^{-3}	0.1×10^{-3}
Lubricated	100	20	2	0.2

Note: These are maximum rates tor sharp fresh abrasive surfaces. After wear and clogging, abrasive wear rates are generally reduced by up to a factor of 10.

ADHESIVE WEAR OF THE HARDER MATERIAL

For materials of different hardness sliding against each other, Equation 1 gives the wear of the softer one. There has been relatively little study of the wear of the harder material, but a good estimate may be obtained by the following procedure. If the harder surface is harder by less than a factor of three, its wear volume will be less than that of the softer surface as the hardness ratio squared. If the harder surface is more than a factor of three harder, its wear will be less by three times the hardness ratio.

Illustrative Example 2
Problem

In a certain system an aluminum alloy (hardness 60 kg/mm^2) slides against tungsten (hardness 480 kg/mm^2). After a certain period of time 10 mg of aluminum are worn away. Estimate the wear of the tungsten.

Solution

Since the density of aluminum is 2.7 mg/mm^3, wear of the aluminum is 3.70 mm^3. Tungsten is 8 times harder than aluminum, and hence its wear is less by a factor of 3 × 8, or 24. Thus, the volume wear of the tungsten is 0.154 mm^3. Since the density of tungsten is 18.8 mg/mm^3, expected weight loss of the tungsten will be 2.9 mg.

ABRASIVE WEAR

Abrasive wear, the removal of material by a plowing, cutting, or scratching process, also obeys Equation 1. The wear coefficient is determined mainly by the abrasive geometry, i.e., the effective sharpness of the abrasive, and to a smaller extent by the lubrication, which determines the ease with which wear debris can be removed from the sliding interface.

Typical wear coefficient values are shown in Table 4. Abrasive wear only occurs when the sharp material, present as protuberances or as loose grains, has a higher hardness than the surface subject to abrasive wear. Abrasive wear coefficients tend to be higher than adhesive wear coefficients, certainly in the case of lubricated surfaces. Thus, when abrasive wear and adhesive wear occur together, abrasive wear is generally predominant.

CORROSIVE WEAR

This is a very complicated form of wear, in that corrosion occurs and then the products of corrosion are worn away. Many corrosion products have some lubricating ability which also affects the wear rate. Quantitative analyses of corrosive wear have generally resulted in very complex expressions,[11] and nothing as simple as the wear equation can adequately characterize corrosive wear.

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The least wear coefficient resulting from the combined effects of corrosion and adhesive wear is about 10^{-6}, but as temperature is raised and corrosion becomes rampant, the wear coefficient increases to 10^{-2} and even higher. For well-designed combinations of lubricant, surfaces, and temperature, corrosive wear coefficient values in the range of 10^{-4} to 10^{-5} are frequently observed.

SURFACE FATIGUE WEAR

This is generally observed only in systems undergoing combined sliding and rolling, such as ball bearings, gears, cams, and automotive valve lifters. It is characterized by an induction period during which microcracks grow on and under the sliding surfaces without any readily detectable wear. Then suddenly one or more large wear particles are produced. This process is not amenable to treatment by expressions such as Equation 1 which assume that wear is a steady continuous process.

APPENDIX: SOME TYPICAL USES OF WEAR COEFFICIENTS

Three examples from Reference 12 indicate ways in which wear coefficients can be used in evaluation of worn sliding surfaces. A knowledge of the wear coefficient value can be used to eliminate one or more possible modes of wear, and this can frequently be done even though typically there is an uncertainty factor of ± 4 in the value of wear coefficient.

Example 1: Wear of Hollow Jet Engine Turbine Blades

Certain jet engine turbine blades are cast hollow, a soft metal tube is fitted inside each blade, and cooling air is passed through the space between the tube and the blade. The tube was wearing away rather rapidly. The first hypothesis was that slip between the tube and the turbine blade occurred because the turbine blade was vibrating, and consequent sliding action led to the observed wear. The likely loads, amplitudes, and frequencies suggested a wear coefficient of 2.4×10^{-4}. The second theory was that slip occurred as result of a thermal expansion mismatch between the tube and blade. Knowing the number of thermal cycles the engine had undergone, one could compute a wear coefficient of 1.1.

Since adhesive wear coefficients of this magnitude do not exist, the thermal expansion theory was eliminated. If the other theory is correct, then Table 2 suggests that the blade and tube (which in terms of metallurgical compatibility represented a ‘soluble’ combination) operated in a region of poor lubrication, or else rampant corrosive wear was occurring. Actually, the latter was a correct description. The blades and tubes were at very high temperatures, and the protective oxide layers were being continually worn off.

Example 2: Unusually Severe Wear of Railroad Rails

Excessive wear of railroad track carrying heavily loaded ore cars in Canada was noted. On a sharply curved section of track, the rail wore down to an unsafe condition in only about a year.

Approximation of the amount of slip or sliding between the train wheels and the track (pure rolling causes essentially no adhesive wear) indicated a wear coefficient of 2×10^{-4}. Table 2 suggests that for identical metals (in terms of composition, railroad rails and wheels are very similar steels), this wear coefficient is characteristic of “poor lubrication”. This seems not unreasonable for marginal lubrication from rainfall and contamination. Thus, it was not necessary to postulate any new and unusual phenomenon; simply the amount of traffic and the slippage associated with the sharp curves had produced this large amount of adhesive wear.

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Example 3: Excessive Wear of the Ways of a Cold Deformation Processing Machine

Sliding occurred between a high-carbon steel die and an aluminum bronze way at reasonably high speeds and loads. A good lubricant was provided. The aluminum bronze was wearing rather rapidly, the wear coefficient being 5×10^{-5}.

The combination of iron against copper is of intermediate solubility and the use of a steel as against iron, and of aluminum bronze as against copper, does not change the rating. For a combination of intermediate solubility a wear coefficient of 5×10^{-5} indicates poor lubrication. In this case the machine design was such that the sliding surfaces became overheated, and consequently the 'good' lubricant behaved like a 'poor' one. The remedy: either improve the cooling, or use a lubricant with better performance at high temperatures.

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